

# Laminar, Two-dimensional Flow Past Cylinder

## 1 Introduction

This case provides a description for two-dimensional flow past a cylinder case with constant properties.

## 2 Domain

The two-dimensional geometry for the midterm assignment is captured in Figure 1 where a hybrid meshed domain is noted.

The top and bottom surfaces are slip (or zero tangential stress) implemented as a “symmetry” boundary condition; the left boundary represents an inflow condition specified velocity,  $u_x = U_\infty = 1$ . The right boundary condition is open, with a specified static pressure. The cylinder wall boundary condition is no-slip and specified to be zero. Flow past a rotating cylinder can be modeled by adding a rotational no-slip velocity. Properties for density and viscosity are 1.2 and 0.008, yielding a Reynolds number of 150 for the unity sized cylinder diameter.

## 3 Theory

The variable-density low-Mach equation set is defined by the continuity and momentum equation,

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_j}{\partial x_j} = 0. \quad (1)$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_j u_i}{\partial x_j} - \frac{\partial \sigma_{ij}}{\partial x_j} = 0. \quad (2)$$

In the above equation,  $\rho$  is the fluid density and  $u_j$  is the fluid velocity. The stress tensor is provided by

$$\sigma_{ij} = 2\mu S_{ij}^* - P\delta_{ij}, \quad (3)$$

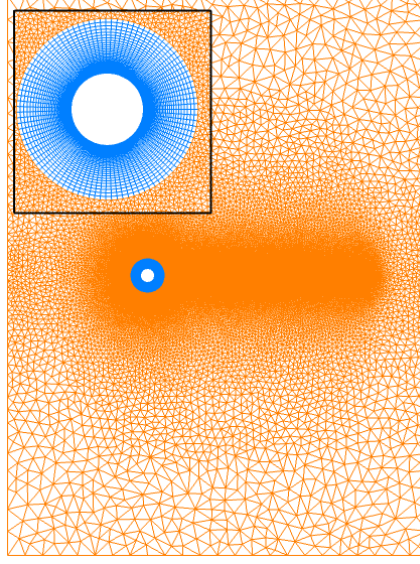


Figure 1: Two-dimensional flow past cylinder hybrid geometry (Quad4 and Tri3) in which the diameter of the cylinder,  $D$ , is unity.

where the traceless rate-of-strain tensor is defined as

$$S_{ij}^* = S_{ij} - \frac{1}{3}\delta_{ij}S_{kk} = S_{ij} - \frac{1}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}.$$

In a low-Mach flow, the above pressure,  $P$ , is the perturbation about the thermodynamic pressure,  $P^{th}$ . The above system can be simplified for a div-free velocity field with constant density.

Although the properties are constant, the baseline case activates a passive scalar,  $Z$ , that is defined as the mixture fraction. The value of  $Z$  varies between zero and unity and can be viewed in an analogous manner as a mass fraction. The transport of  $Z$  is given by,

$$\frac{\partial \rho Z}{\partial t} + \frac{\partial \rho u_j Z}{\partial x_j} + \frac{\partial q_j}{\partial x_j} = 0, \quad (4)$$

where  $q_j$  is the diffusive flux vector given by  $q_j = -\rho D \frac{\partial Z}{\partial x_j}$ ;  $D$  is the diffusivity (units of  $m^2/s$ ) whose value is closed by a constant Schmidt number  $\rho D = \frac{\mu}{Sc}$ . In this particular input file, the Schmidt number is 0.9, and the value at the cylinder surface is set to unity, while the inflow and open far field entrainment value is zero. Therefore, the passive scalar  $Z$  acts to be transported to highlight the vortical flow exhibited by the vortex street. Given that the mixture fraction does not couple to the equations of motion, the boundedness of this variable, i.e., the realization of  $0.0 \leq Z \leq 1.0$  does not affect the primary

flow field. Therefore, modification of this equation’s advection stabilization form (while monitoring the amount of times the variable is clipped), allows a perspective as to the effectiveness of the stabilization (see the line command *output\_clipping\_diagnostic : yes*).

## Introduction

The flow of a liquid or gas past a circular cylinder is ubiquitous in engineering. Examples include the flow of a river current past a bridge support column, or wind blowing past a wind turbine tower or cylindrical water storage tank. This flow is representative of a broad class of flows called “bluff-body” flows. In a bluff body flow, the oncoming fluid at first follows the contours of the body, then at some point separates from the body and creates a wake of relatively low-momentum fluid behind the body. This wake is often of prime importance in engineering of bluff-body systems. It is responsible for creation of a large drag force (force opposing the fluid motion), and can also be responsible for creation of forces on the body that fluctuate in time (also called unsteady forces). The unsteady forces can be oriented both along the wind axis (drag) or perpendicular to the wind axis (lift). Unsteady wakes can also be a source of sound; examples include the wake of aircraft landing gear or “singing” power cables in a strong breeze.

The behavior of a bluff-body flow depends on a non-dimensional number called the Reynolds number. The Reynolds number is defined as:

$$Re \equiv \frac{\rho U_{\infty} L}{\mu}. \quad (5)$$

Here,  $\rho$  is the density of the fluid,  $U_{\infty}$  is the oncoming fluid velocity relative to the body, or “free-stream” velocity,  $L$  is a characteristic length scale associated with the size of the body, and  $\mu$  is the fluid viscosity. For a circular cylinder,  $L$  is usually taken to be the diameter of the cylinder,  $D$ . The Reynolds number can be thought of as the ratio of inertial forces to viscous forces in a flow. An example of a low-Reynolds number flow is a marble dropped in a jar of honey. An example of a high-Reynolds number flow is a commercial airliner flying at cruise. For flows where the fluid velocity is much smaller than the speed of sound, the Reynolds number is a similarity parameter; that means any two flows with the same geometry and same Reynolds number behave exactly the same.

Now, back to the bluff-body wake. The behavior of this flow can be dramatically different depending on the Reynolds number. Take the circular cylinder. For very low Reynolds number ( $Re < 50$ ), the flow is steady; in other words, the fluid velocity at any point in space near the cylinder does not vary in time. The wake consists of two symmetric recirculation regions downstream of the cylinder, as shown in Figure 2. As the Reynolds number increases (think of the fluid speeding up as the cylinder size and fluid properties are kept the same), the wake behind the cylinder becomes unsteady. Pockets of swirling fluid, called

vortices (plural of vortex), are shed from the cylinder and are swept downstream. For  $50 < Re < 200$  this wake remains two-dimensional. Vortices are shed from either side of the cylinder in an alternating pattern called a “vortex street,” as shown in Figure 3. This shedding phenomenon causes unsteady lift and drag forces to act on the cylinder at a characteristic frequency,  $f$ , called the “shedding frequency.” It is convenient to non-dimensionalize this frequency as follows:

$$St \equiv \frac{f D}{U_\infty} \quad (6)$$

$St$  is called the Strouhal number, and is a function of the Reynolds number.

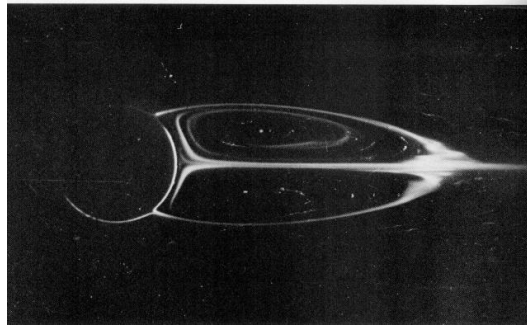


Figure 2: Flow past a circular cylinder at  $Re = 41$ , from a flow visualization experiment. The flow is from left to right. From Van Dyke, *An Album of Fluid Motion*, 1982.

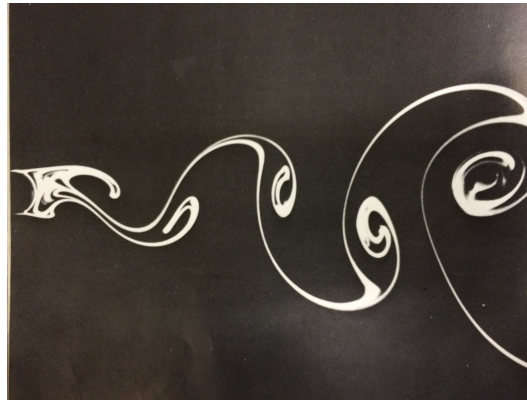


Figure 3: Flow past a circular cylinder at  $Re = 140$ , from a flow visualization experiment. The flow is from left to right. From Van Dyke, *An Album of Fluid Motion*, 1982.

As the Reynolds number continues to increase, more complex flow behavior is observed. We will not concern ourselves with the higher Reynolds number

regimes, but the interested reader is encouraged to investigate this further on their own.

## Quantities of Interest

In any engineering analysis, we must define the relevant Quantities of Interest (abbreviated QoI's), which are the analysis outputs that we are interested in predicting. For the circular cylinder flow, we will define several:

- Time-averaged drag coefficient,  $\overline{C_d}$
- Strouhal number,  $St$
- Root-mean-square of the lift coefficient fluctuation,  $C'_l$

We defined the Strouhal number earlier. The drag coefficient is defined as:

$$C_d \equiv \frac{F_d}{1/2\rho U_\infty^2 D}. \quad (7)$$

$F_d$  is the drag force of the fluid acting on the cylinder. This force is comprised of two components: the pressure drag, resulting from the distribution of fluid pressure along the surface of the cylinder; and the viscous drag, resulting from friction as the fluid flows past the surface.

Similarly, the lift coefficient is defined as:

$$C_l \equiv \frac{F_l}{1/2\rho U_\infty^2 D}. \quad (8)$$

$F_l$  is the lift force, or force of the fluid acting in a direction perpendicular to the oncoming flow.

A sample passive scalar mixture fraction Nalu result for the  $Re = 150$  is shown in Figure 4, while in Figure 5, the drag coefficient as a function of Reynolds number, extracted from Baracu and Bosneagu (2019), is provided. The coarse mesh for the Nalu simulation is provided for a reference.

## 4 Discussion Points

- Compare timing between EBVC and CVFEM. Comments on speed?
- Modify the Reynolds number 10x smaller, 10x larger and report general findings. As you change the Reynolds number, make sure that you adjust the initial time step specification such that the first Courant number reported in the log file is not greater than 2.0.
- Explore Peclet blending for both velocity and mixture fraction.
- Explore laminar Schmidt number (nominal value of 0.9), 10x smaller; 10x larger.

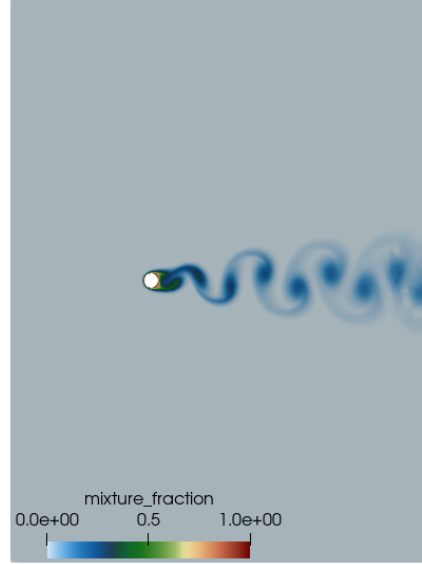


Figure 4: Two-dimensional passive scalar representation for a  $Re = 150$  case in which a Schmidt number of 0.9 is specified to compute the diffusive flux coefficient.

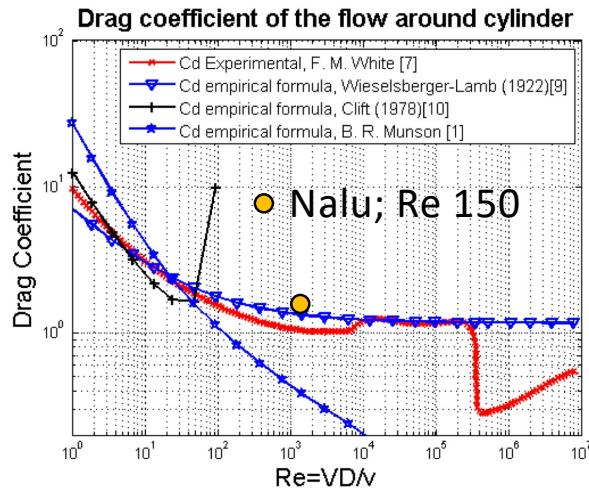


Fig. 7 – Comparison of experimental results with empirical formulas of prediction for the drag coefficient of flow around cylinder

Figure 5: Drag coefficient for flow around a cylinder from Baracu and Bosneagu, *Scientific Bulletin of Naval Academy, Boll XXII*, 2019.

- Monitor the total amount of instances in which the mixture fraction is non-monotonic.

The maximum and minimum clipped value can be provided in the MixtureFraction equation system via the specification of a deviation from the monotonic range (zero and unity) via, *clipping\_delta* : 0.0, where 0.0 is the current default level. When clipping, how does nonlinear convergence behave?

- Explore various quantities of interests (QoIs), including: mean and instant drag coefficient; mean and instant lift coefficient.

Note: *vortexStreetCVFEM.Quad4.dat* that provides forces and moments on the cylinder surface. For QoIs above, at the nominal Reynolds number, what is the effect of: a) Mesh refinement; see: *examples/street/circular\_cylinder\_medium.exo*, b) First-order time vs second-order time: *second\_order\_accuracy* : *yes/no*, c) Changing the number of nonlinear iterations from 2 to 5, and 10: (note the convergence within each step): *max\_iterations* : 2,4,8, d) Linear solver tolerance: tolerance: 1e-5, e) Usage of limiters and the effect

- (Optional) Compute a FFT for either mixture fraction or velocity at select locations/points in the domain.
- (Optional) For CVFEM, deactivate upwind blending for mixture fraction via the designation of the tanh transition, *peclet\_function\_tanh\_transition*, to something large, i.e. 1e6. Activate a nonlinear stabilization operator for mixture fraction using a new *element\_source\_terms* block while ensuring that *NSO\_2ND* has been activated (see below for an input file example).

The input file change for the nonlinear stabilization operator is as follows:

```
solution_options :
  name: myOptions
  turbulence_model: laminar

  use_consolidated_solver_algorithm: yes
  use_consolidated_face_elem_bc_algorithm: yes

options :
  - element_source_terms :
      momentum: [lumped_momentum_time_derivative ,
                  upw_advection_diffusion]
      continuity: [advection]
      mixture_fraction: [lumped_mixture_fraction_time_derivative ,
                          upw_advection_diffusion , NSO_2ND]
```

You may also remove all *upw\_* options in the activated element source terms block that results in a purely non-Peclet blending approach:

```
solution_options :
  name: myOptions
  turbulence_model: laminar

  use_consolidated_solver_algorithm: yes
  use_consolidated_face_elem_bc_algorithm: yes

options :
  - element_source_terms :
      momentum: [lumped_momentum_time_derivative ,
                  advection_diffusion , NSO_2ND]
      continuity: [advection]
      mixture_fraction: [lumped_mixture_fraction_time_derivative ,
                          advection_diffusion , NSO_2ND]
```

Using the above block, all of the peclet blending options will be ignored.